ESA GSTP De-Risk:
Development of an Electric Pump for a Plug-in Hybrid Rocket Propulsion System

Final Presentation

ESA Contract No. 4000140571/22/NL/GLC/cb

2024-05-10

HyImpulse

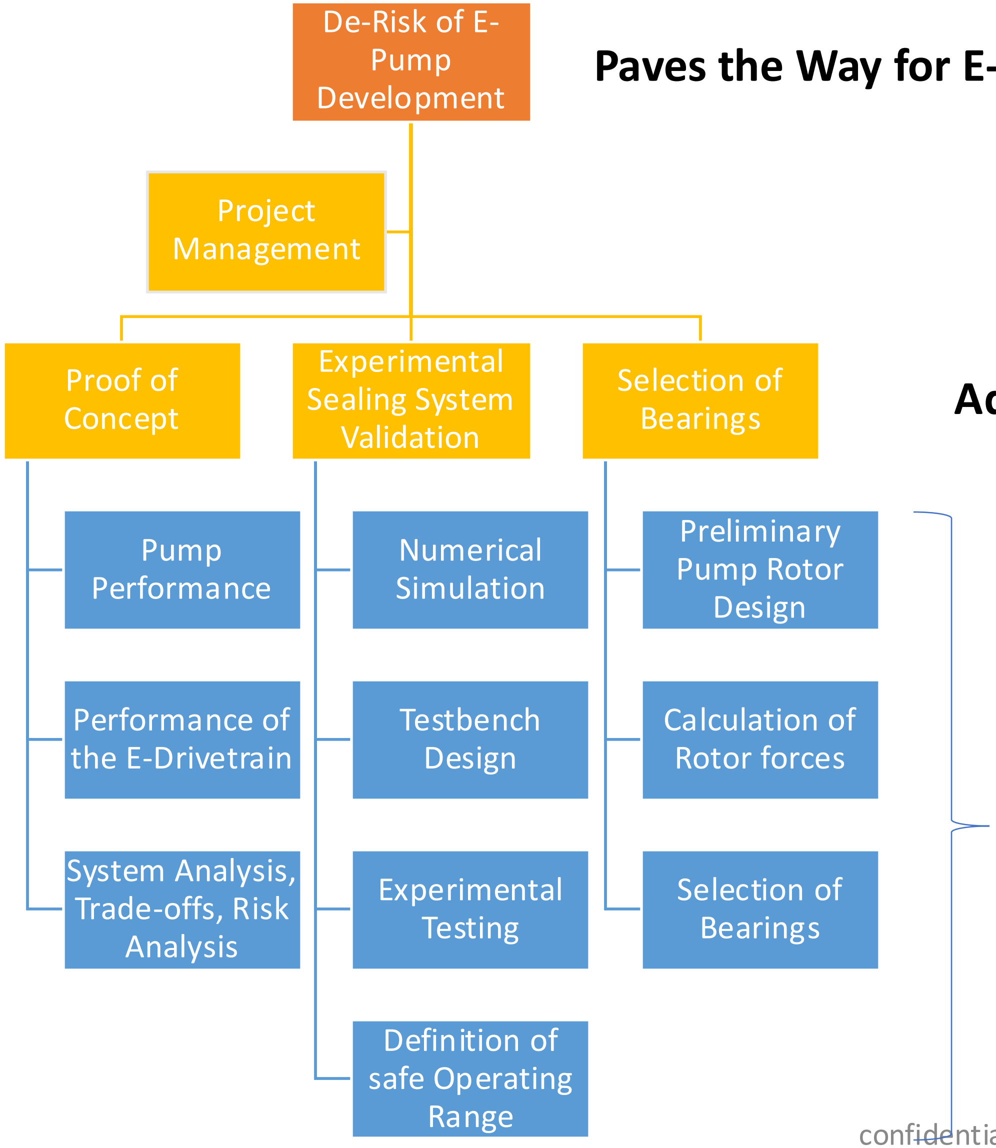
Project goal and work packages

Goal: to pave the way to technological development of an Electric Pump dedicated to Hybrid Rocket Propulsion

How: by identifying, addressing and resolving factors of risk

Pave the Way for E-Pump Development		
Identification of Risks →	Assessment of Risks →	**Reduction of Risks**

Project goal and work packages

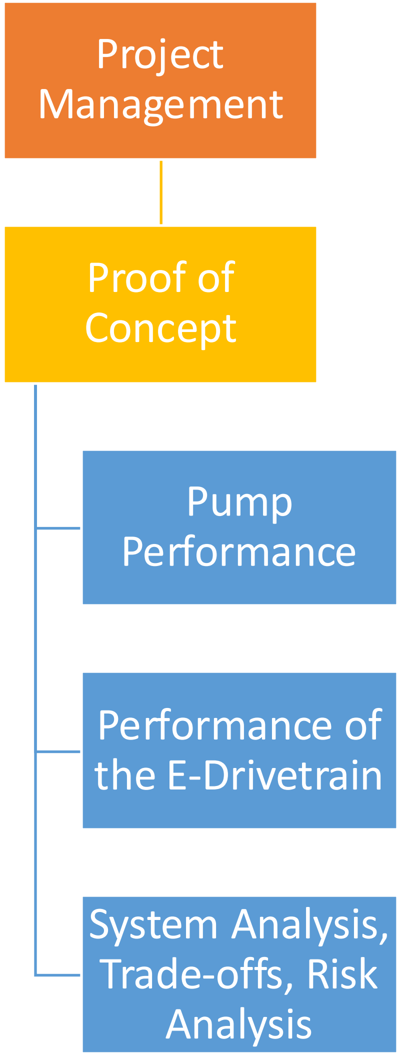


Paves the Way for E-Pump Development ✓

Adresses main risks of E-Pump Development ✓

Serves the de-risking ✓

WP2000 : Proof of Concept



❖ **Inputs:**
- Requirements for the 3rd Stage Propulsion Document
- Preliminary Assessment for the Electric Powertrain for the 3rd Stage (Report)

❖ **Goal:**

a) To perform a feasibility analysis of the Electric Powertrain for the 3rd Stage of the SL-1 hybrid rocket,

b) To determine range of electric drivetrain parameters that will be used for detailed development of the Pump, and

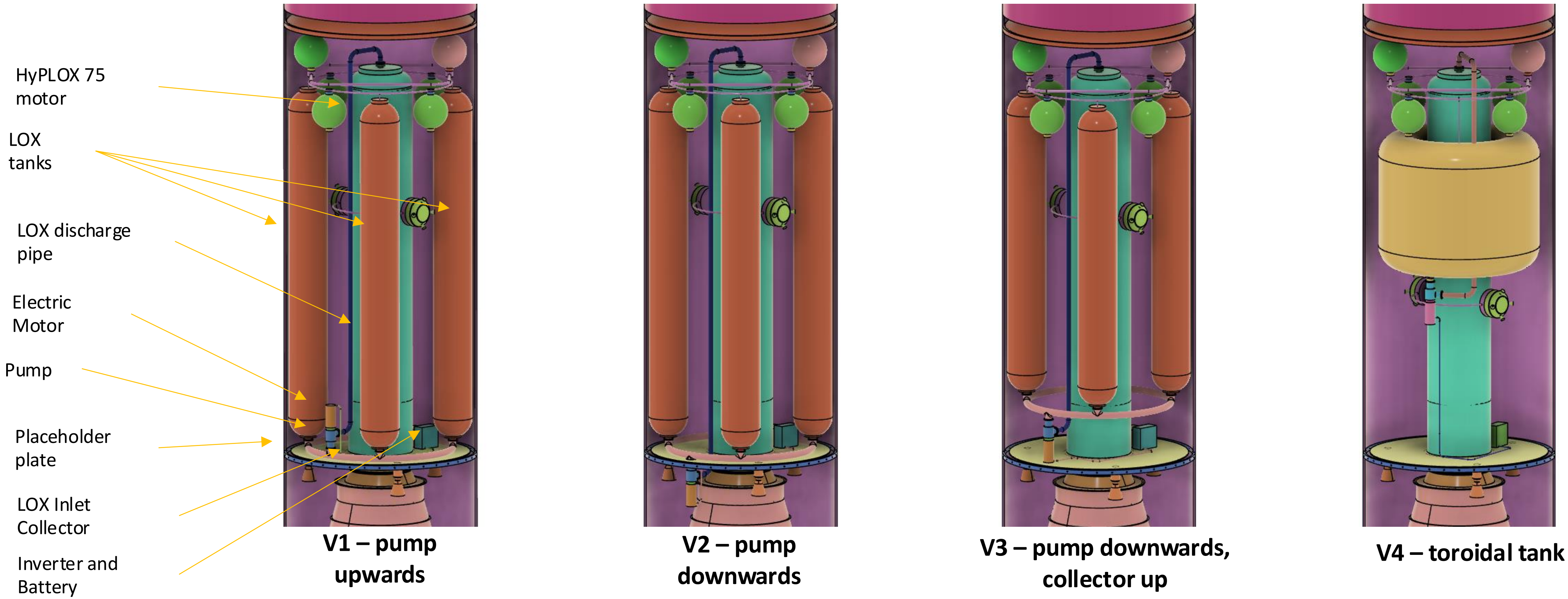
c) To identify the development risks and challenges.

❖ **Tasks:**
- <u>Preliminary analysis of the Pump Performance</u>. Based on the requirements for the 3rd stage propulsion system, the expected configuration and performance of the LOX pump will be estimated.
- <u>Performance of the Electric Drivetrain</u>. Estimated pump performance will be used for the final selection of the electric drivetrain components (Electric Motor, Inverter, Battery). For this HyImpulse will run consultations with earlier identified suppliers. The topic of potential challenges and required future works will be also discussed. The outcome of this task should be a list of components that will be used in the electric drivetrain.
- <u>System Analysis, Trade-offs, and Analysis of Risks</u>. The performance ranges and particularities of the selected drivetrain components will be analyzed when working as one system. The configuration of parameters that give the highest performance as well as the operational envelope for the propulsion system will be determined. This will be used as a limiting factor during the further development of the pump. Additionally, challenges and possible risks for the detailed system development will be identified.

WP2000 : Preliminary analysis of pump performance

<u>Inputs</u>: SL1 upper stage mission profile and required hybrid motor performance (chamber pressure, mass flow)

4 possible system architectures are analysed: they differ in tank arrangement, pump position and orientation which result in different head, suction performance, required torque and rpms.



V1 – pump upwards

V2 – pump downwards

V3 – pump downwards, collector up

V4 – toroidal tank

WP2000 : Preliminary analysis of pump performance

Each architecture results in pump requirements which trickle down to motor, inverter and battery requirement.

Parameter	V1 – pump upwards	V2 – pump downwards	V3 – pump downwards, collector up	V4 – toroidal tank
Required pressure rise	43.4 bar	43.8 bar	43.4 bar	41.7 bar
Required hydraulic power	77.4 kW	78.13 kW	77.4 kW	74.4 kW
Estimated pump hydraulic efficiency	0.75			
Required pump power	103.2 kW	104.2 kW	103.2 kW	99.2 kW
Rotational speed	**20 000 rpm**			
Output torque T_L	49.3 Nm	49.8 Nm	49.3 Nm	47.4 Nm
Frictional losses	5 kW			
Frictional torque	2.4 Nm			
Required EM continuous power output	108.2 kW	**109.2 kW**	108.2 kW	104.2 kW
Required EM continuous torque	51.7 Nm	**52.2 Nm**	51.7 Nm	49.8 Nm
Minimum actuation torque	63.6 Nm	**64.1 Nm**	63.6 Nm	61.7 Nm

- **Electric Motor**

Parameter	Requirement
Operation time	120 sec
Rotational speed	20 000 rpm
Power output	110 kW
Continuous torque	53 Nm
Actuation torque	65 Nm

- **Battery**

Parameter	Requirement
Battery power	117 kW
Energy capacity	3.9 kWh
Battery voltage	600-800 V

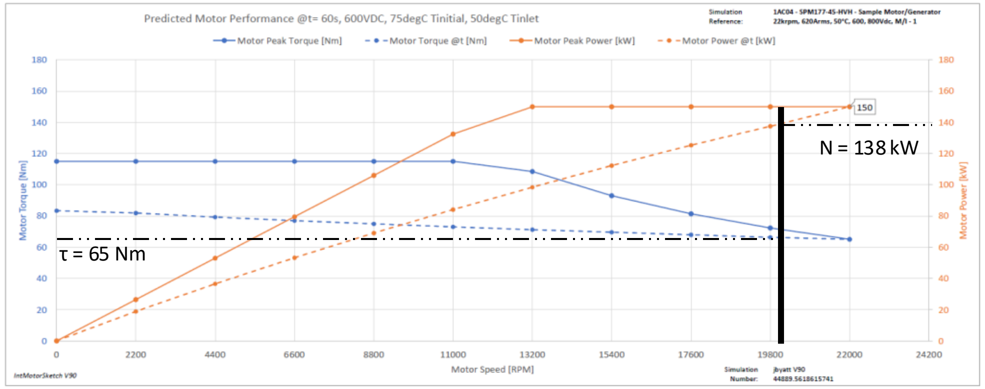
- EM efficiency – 0.96
- Inverter efficiency – 0.98
- Battery efficiency – 1.0 (no cooling required)
- Battery safety factor 1.0 (discharge to 3V)

WP2000 : Drive train performance

HyImpulse’s development strategy relies on splitting the pump system (to be developed internally) and the power train (to be composed of commercially available items).
The requirements obtained allow the selection of components based on performance maps and item weight.

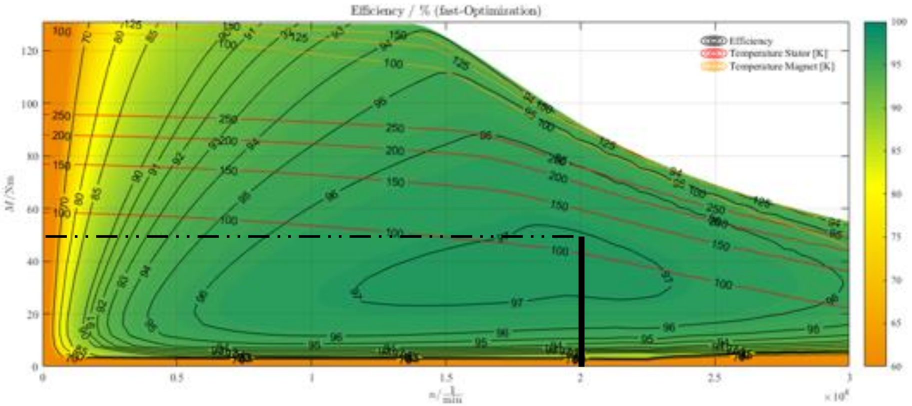
Parameter	Value
Maximum power	150 kW
Maximum Torque	115 Nm
Maximum speed	22 000 rpm
Efficiency at design operating conditions	0.96
Mass	14 kg
Summary power density	10.7 kW/kg
Prototype cost	20 k£
Lead time	30 weeks

Helix SPM-88-120



Parameter	Value
Maximum power	180 kW
Maximum Torque	80 Nm
Maximum speed	30 000 rpm
Efficiency at design operating conditions	0.97
Mass	13 kg
Summary power density	13.8 kW/kg
Prototype cost	25 k€
Lead time	27 weeks

Sci-Mo SY43



WP2000 : Drive train performance

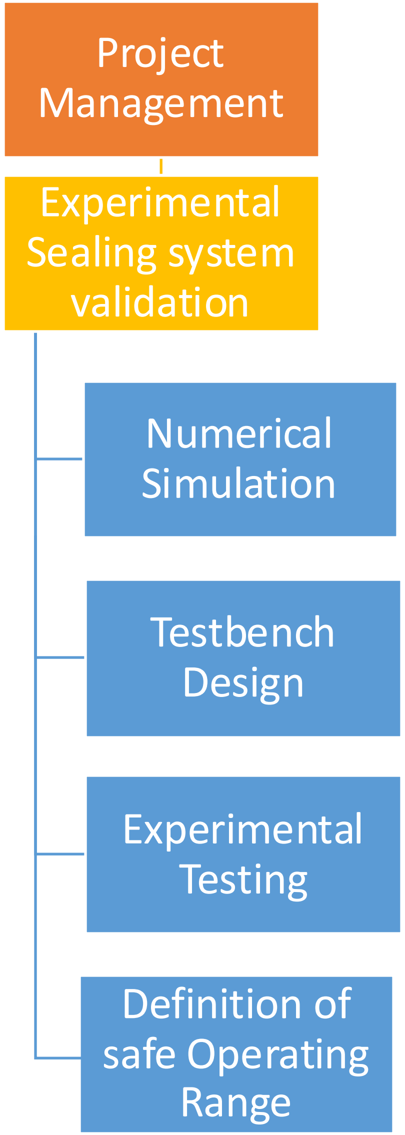
The approach is feasible, and the system can be between 10% and 75% lighter than a turbopump or pressure fed system!

Case	Part	Supplier	Model	Efficiency	Mass
Light	Pump	HyImpulse	–	0.715	15 kg
	Electric Motor	SciMo	SY43	0.97	13 kg
	Inverter	SciMo	ISC2 12-400IC	0.99	6.5 kg
	Battery	EVParts	custom	1	35 kg
	Casing, wires, etc.	–	–	–	5 kg
			Total	**0.69**	**74.5 kg**
Heavy	Pump	HyImpulse	–	0.715	15 kg
	Electric Motor	Helix	SPM-177-45-HVH	0.96	14 kg
	Inverter	Helix	IP MCU 1200-620-02	0.98	6.5 kg
	Battery	WAE	custom	1	60 kg
	Casing, wires, etc.	–	–	–	5 kg
			Total	**0.67**	**100.5 kg**

WP2000 : Identification of risks

- Parallel development strategy requires de-risking of the **sealing** solution proposed. Thermal management of the component is critical because of the risk of auto-ignition in a pure oxygen environment.
- **Bearing elements** are critical, because of high speed, cryogenic temperatures, and poor lubrication.
- **Thermal management of the electric motor** needs to be addressed in the definition of the integrated system.
- **Thermal management of batteries and inverter** needs to be guaranteed, because of the harsh environment in which they will operate

WP3000 : Sealing System Experimental Validation



❖ **Inputs:**

- D2 – System Analysis (Proof-of-Concept) Report

❖ **Goal:**

The goal of this WP is to identify the safe operating range for the proposed sealing system in the relevant environment.The identified sealing operating envelope will be then used as a limiting factor during the further detailed development of the pump.

❖ **Tasks:**

The goal of WP3000 will be reached by the completion of the four tasks:

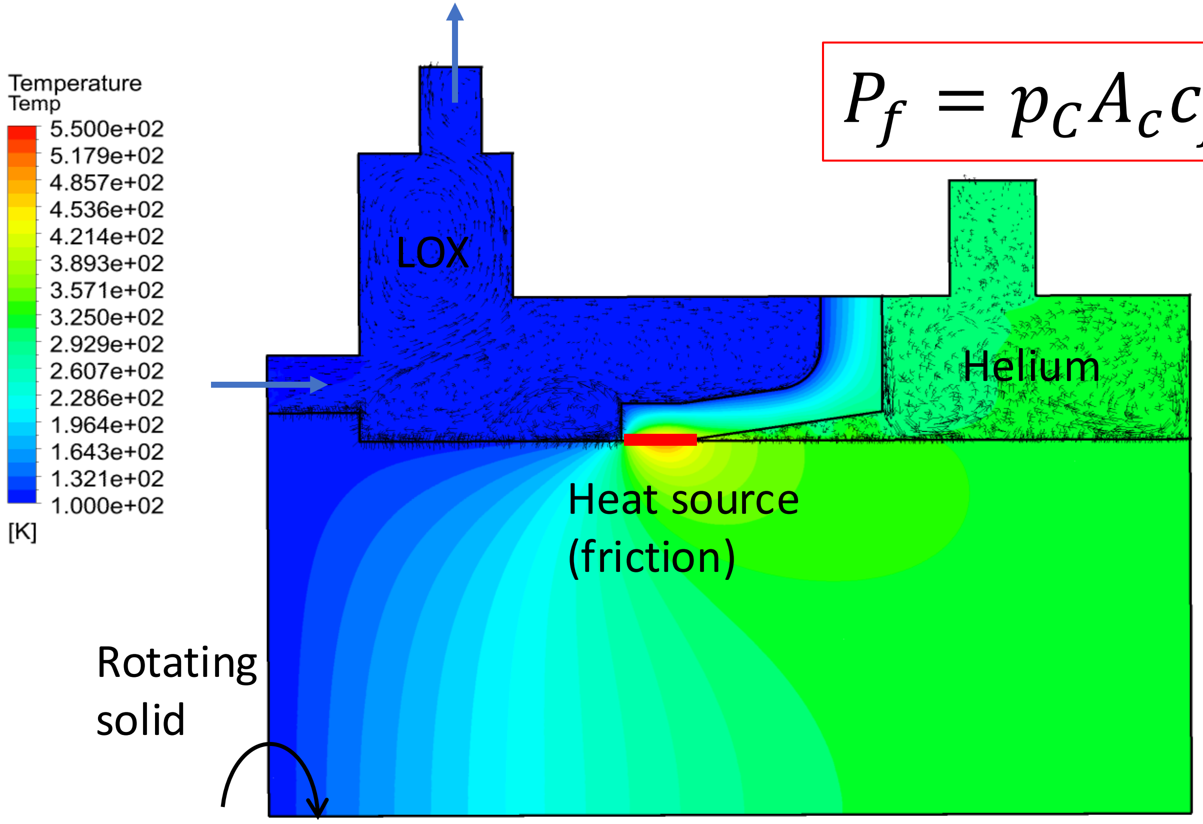
- <u>Numerical Assessment of the Test Envelope</u>. Numerical simulations of the proposed sealing system will be performed. This includes thermal analysis of the sealing surfaces where PV value is an input and temperature is an outcome.
- <u>Testbench Design</u>. A testbench with the capability of operating the proposed sealing system in cryogenic environment at the PV-values identified during the previous task will be designed. All required hardware will be defined, manufactured, bought and assembled to result in a ready-to-use test rig.
- <u>Experimental Testing in a Relevant Environment</u>. This task includes experimental testing of the proposed seal design according to the earlier developed test plan (task 1 of this WP).. A thermal camera will be used to measure the temperature close to the sealing surfaces. This measurement will be then compared to the results of numerical simulations to assess their reliability and to introduce corrections to the numerical model (if needed).
- <u>Identification of the Safe Operating Range</u>. The safe operating range for the proposed sealing design will be identified based on the results of the experimental testing and corrected numerical assessment.

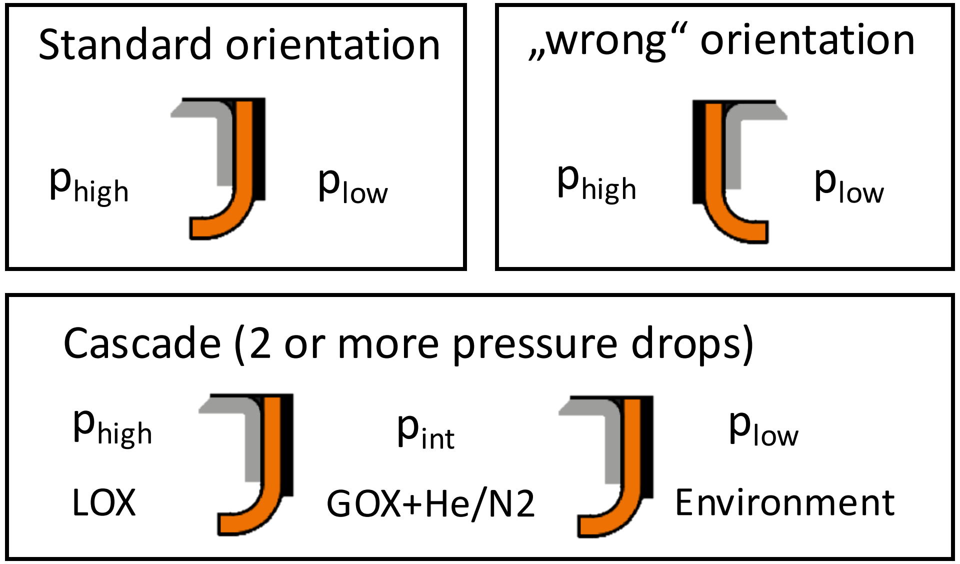
WP3000 : Numerical Simulation

Given pressure and local velocities expected, a lip seal could be used.

The primary limit of the operating range of the lip seal is the contact temperature!

$$P_f = p_C A_c c_f R\omega$$





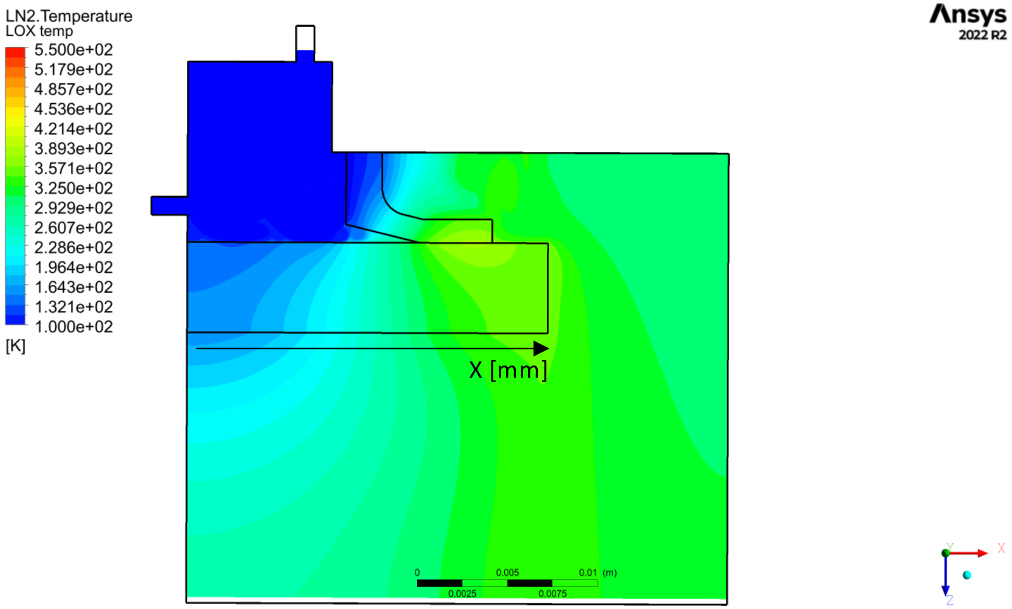
Sealing design chosen : Standard orientation, 1.5mm lip (**type A**)
“Wrong” orientation, 4mm lip (**type B**)
Additional configuration: “Wrong” orientation, 1.5mm lip (**type AB**)

WP3000 : Numerical simulations

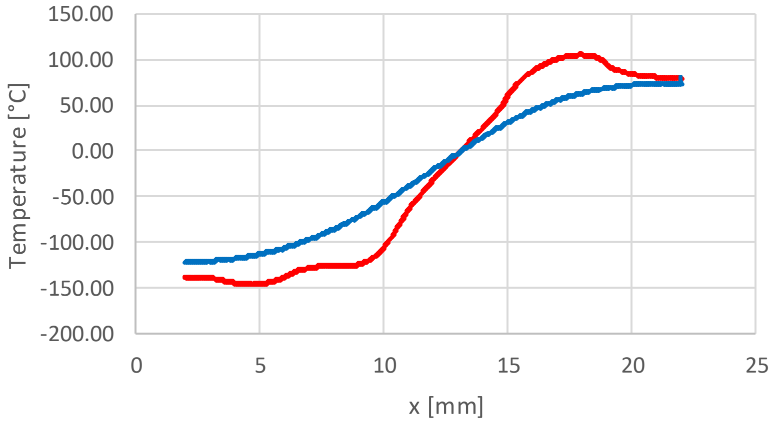
$$P_f = p_C A_c c_f R\omega$$

Friction power is, all things being equal, directly proportional to $p_C R\omega$ -> **p x V** can be used as <u>similarity criteria</u>

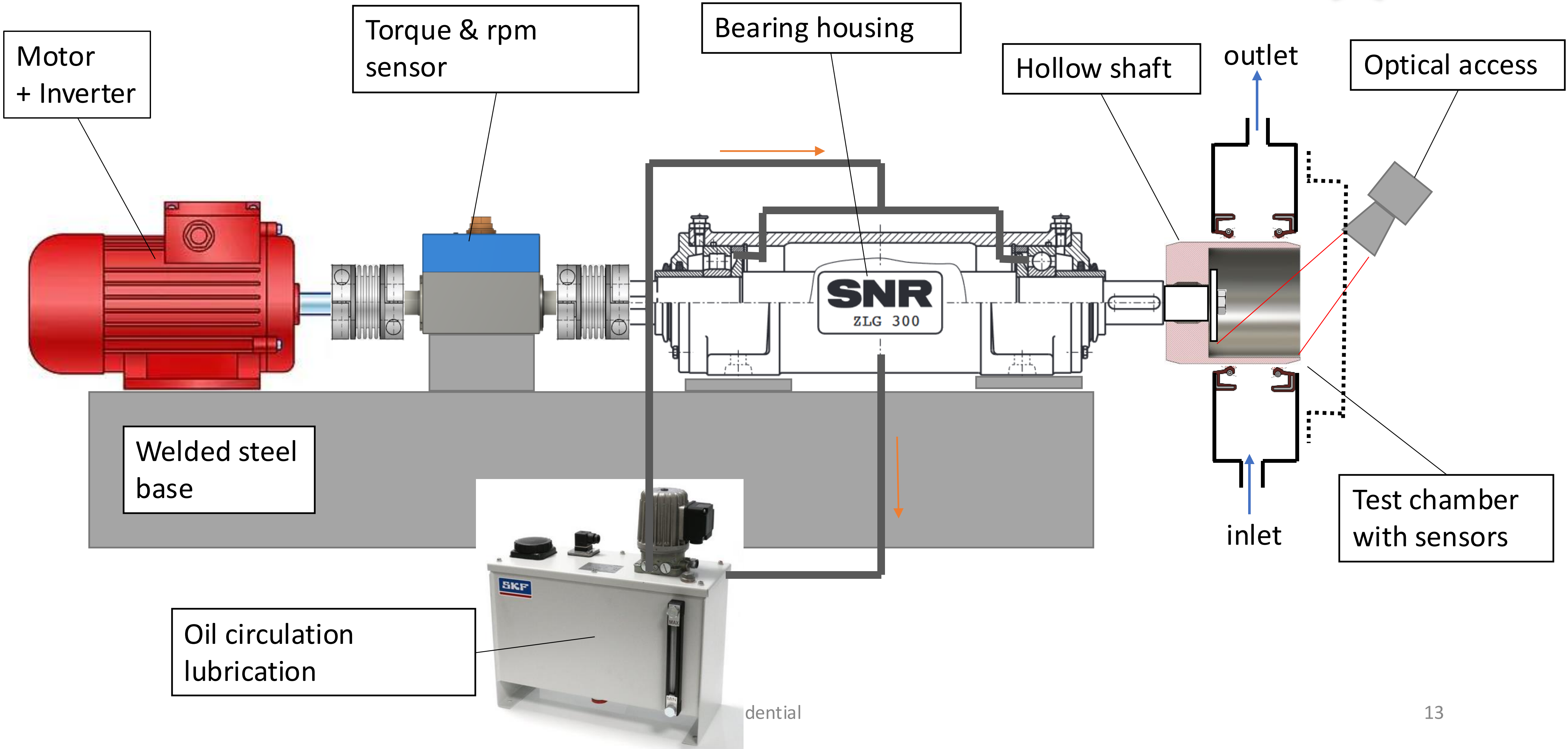
- Numerical and analytical assessment to design seals and evaluate performance
- Test bench to validate empirically in cryogenic environment
- Simulation performed for both pump and test bench geometry confirm that same BCs lead to similar contact temperatures



Test 3.9.3-5 - constant power distribution



WP3000: Test bench design



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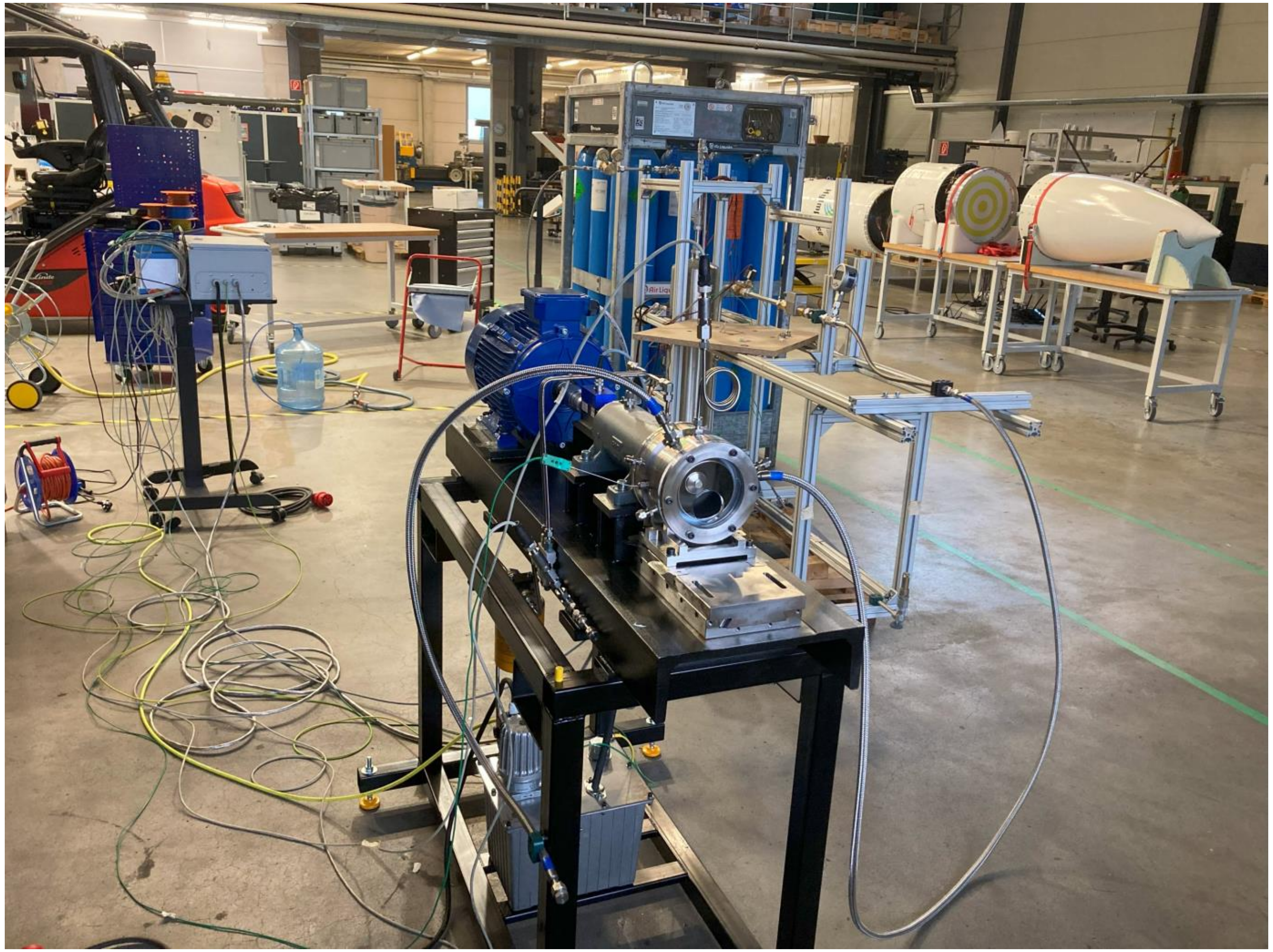
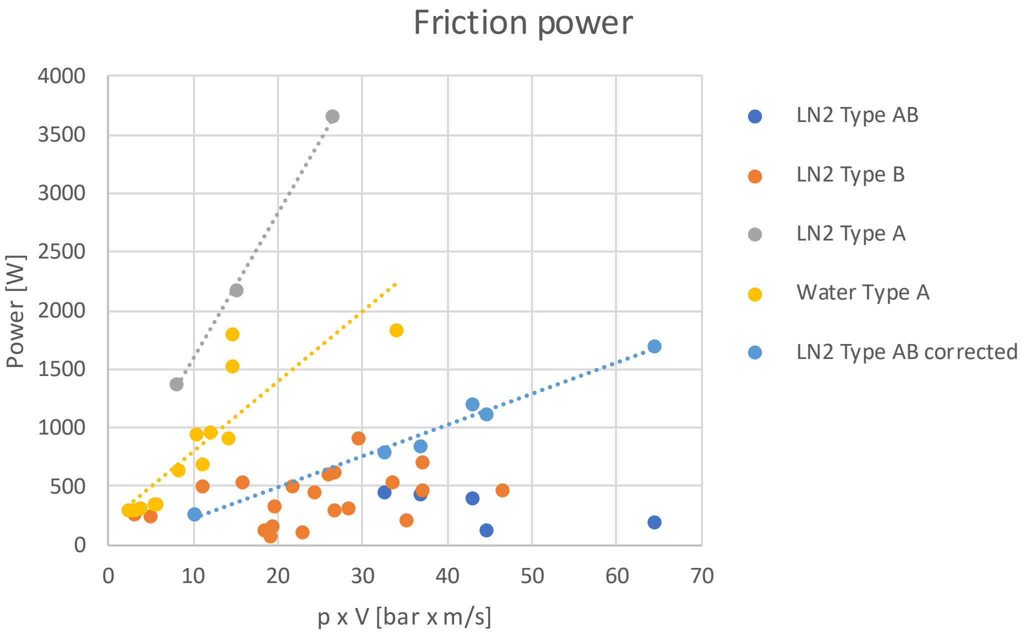
WP3000: Test bench design



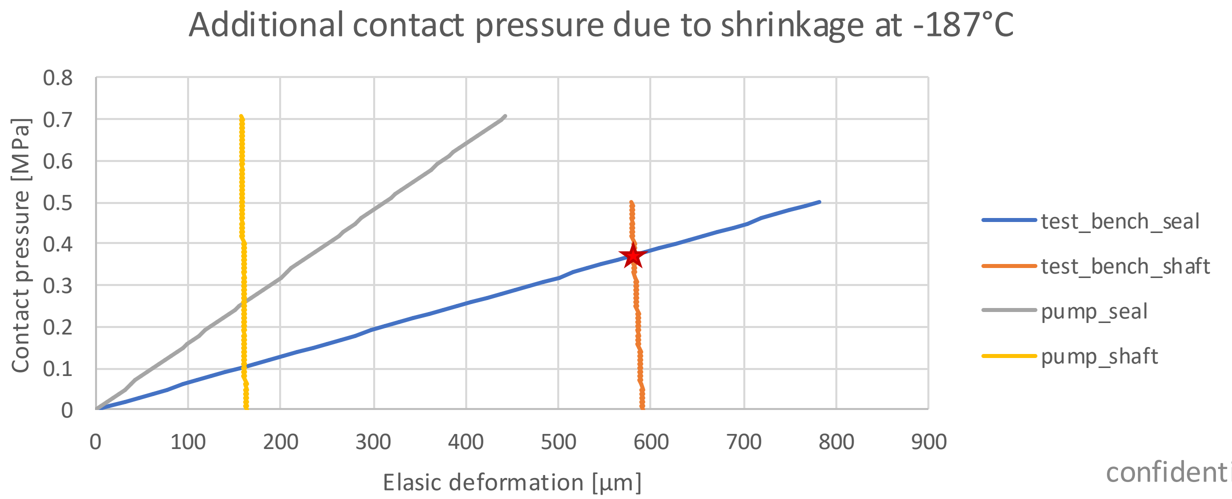
WP3000 : Experimental testing



1. Linear dependence of Power output to p x V holds true, once real effects are accounted for! $P_f = p_C A_c c_f R\omega$

2. Cryogenic conditions increase contact pressure by a non-negligible amount, leading to higher than expected power values

3. Mechanical integrity of the material poses a limit to operations



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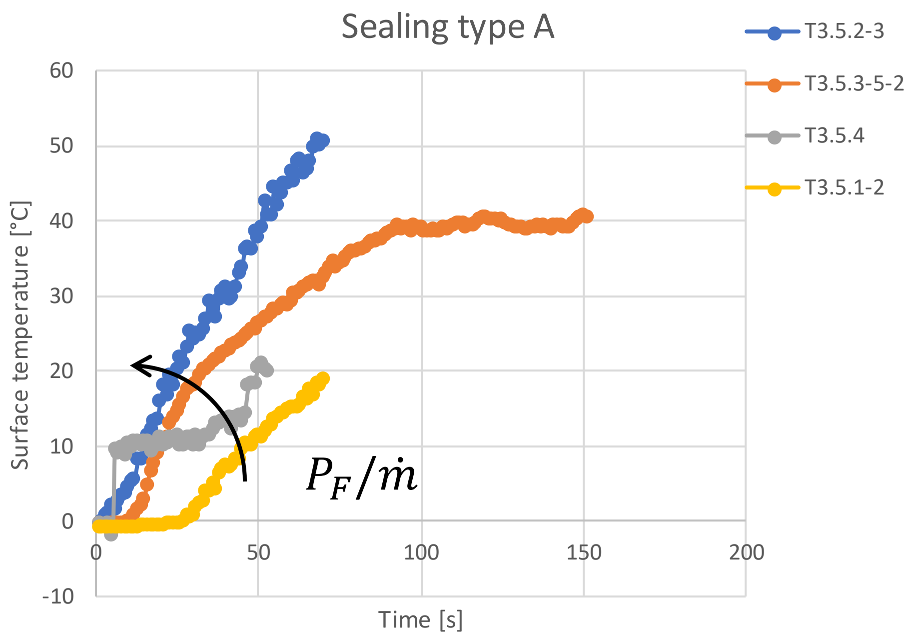
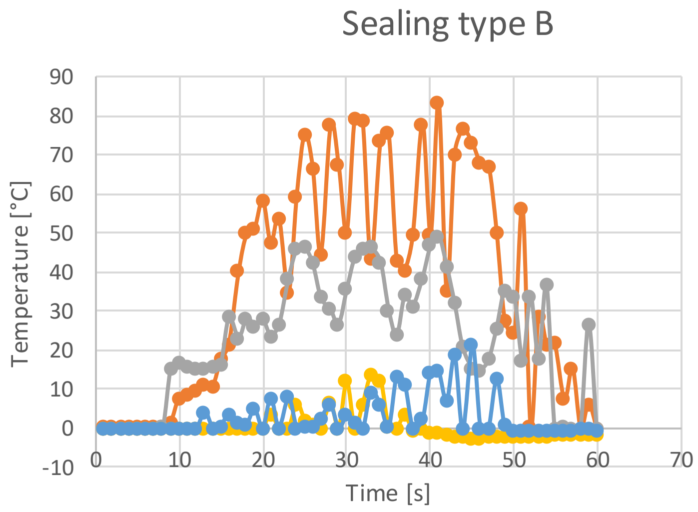
WP3000 : Experimental testing

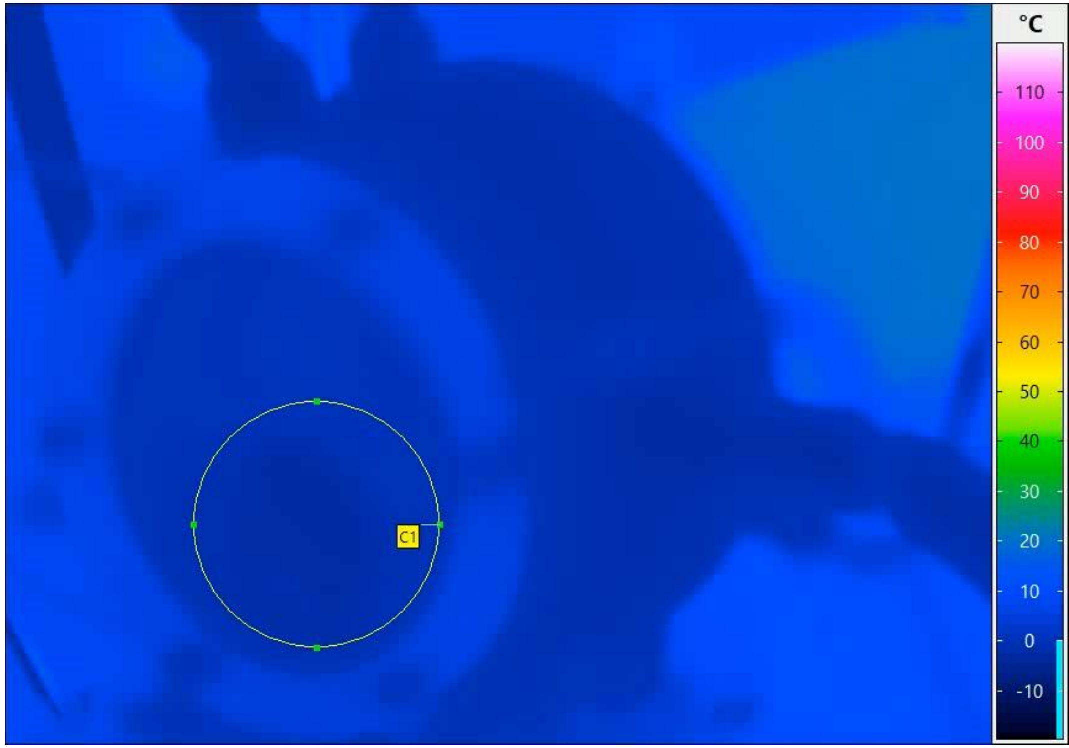


4. The two sealings show different thermal transients – hinting different dynamic behaviours

5. Sealing fails "safely" : leaks before reaching high temperatures, with subsequent cooling of the contact area

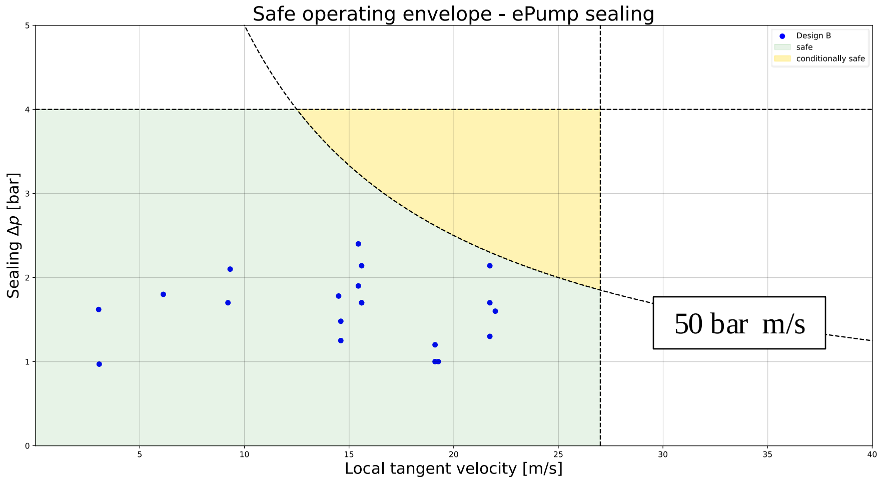


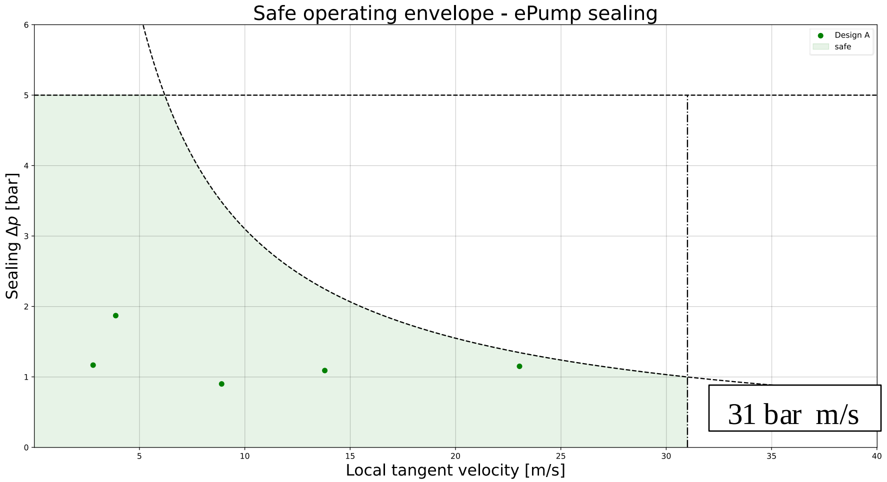
Pulsating behaviour = unstable equilibrium point

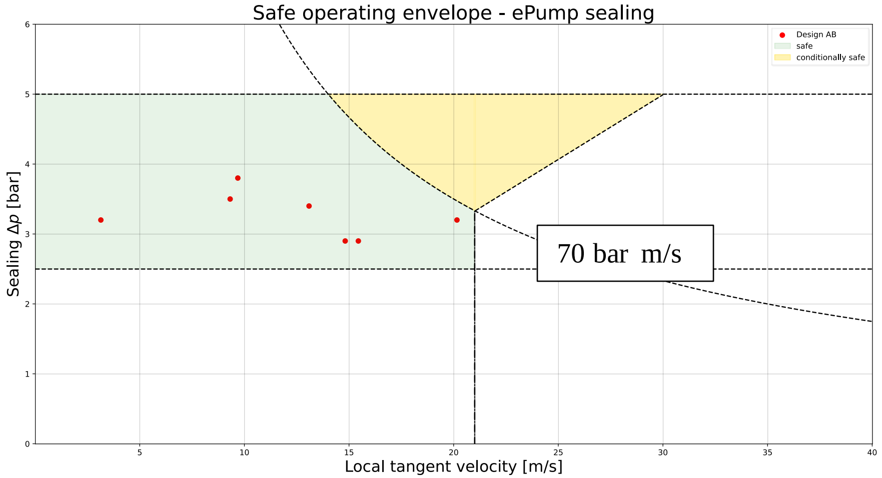


WP3000 : Definition of safe operating envelope

Trends and relations observed during experimental testing allow to validate and update the numerical model.
Based on the maximum temperature threshold criteria, it is possible to define an envelope of safe operating points on a p,V plot.







WP4000 : Preliminary design of Pump

HyImpulse

- Design of pump impeller, volute, and an overall pump structure.
- Derivation of an analytical solution to design pump rotor and volute casing using literature and pre-existing pump design methodology available with HyImpulse.
- Single Performance parameter is defined to score different pump configurations against each other

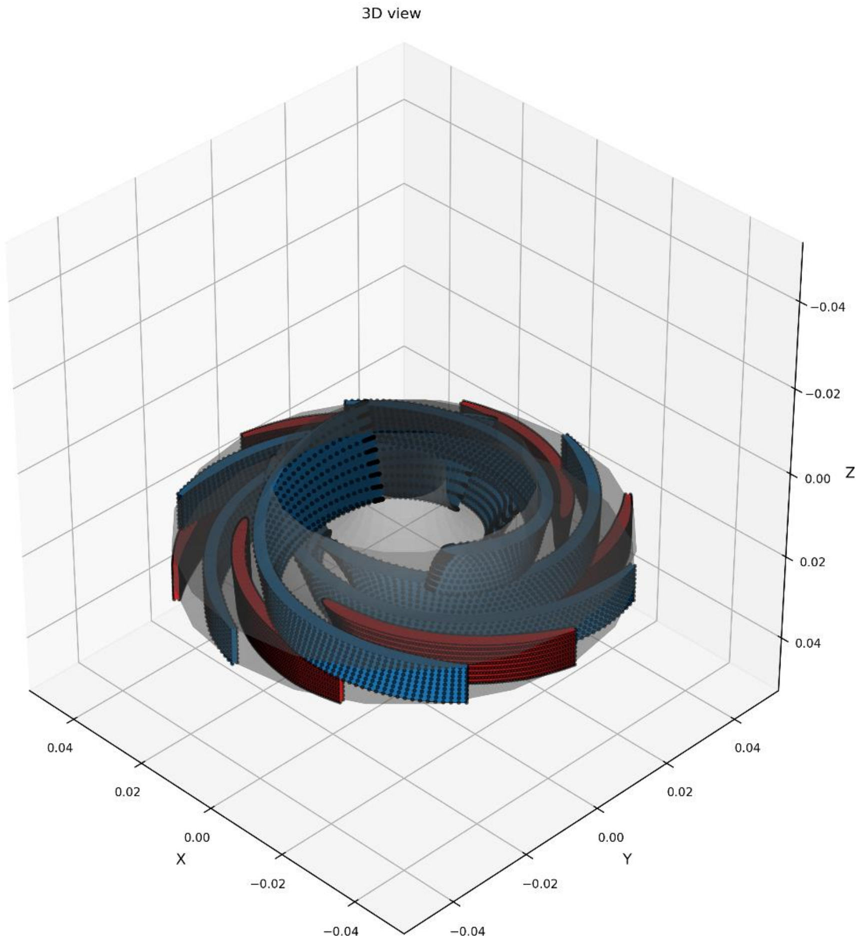
Design parameters	Performance parameters
Impeller eye diameter	Required NPSH ($NPSH_r$)
Number of blades on impeller	Pump efficiency (Hydraulic efficiency η_h, Volumetric efficiency η_v, and Overall efficiency η_0)
Splitter blades on impeller	Power (Hydraulic power and Shaft power)
Splitter blade to main blade length ratio	Nominal blade thickness
Splitter blade to main blade separation ratio	Volute casing thickness
	Estimated leakage

- Available NPSH ($NPSH_a$): Total amount of suction head available at the pump inlet.
- Required NPSH ($NPSH_r$): Minimum suction head required by the pump to operate without experiencing cavitation. (*Pfleiderer* and *Gülich criteria*)

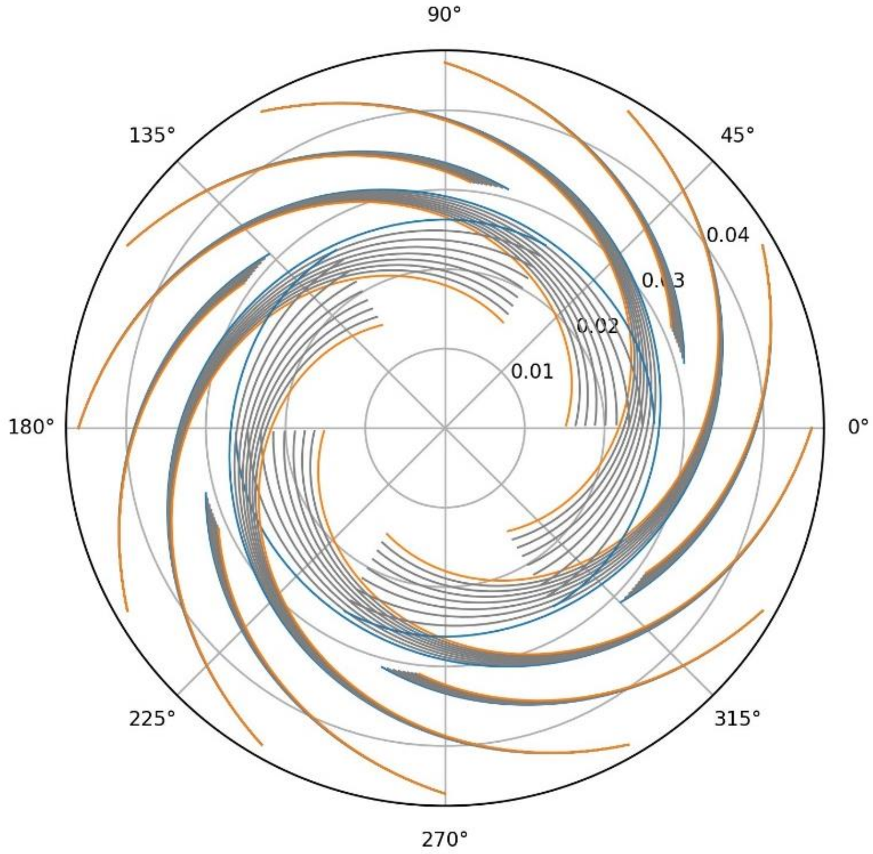
Design parameters			Performance parameters			Single Performance Parameter
			$NPSH_r$ margin		Nominal blade thickness	
Number of blades	Splitter blades (0/1)	Impeller eye diameter (mm)	I	II		
4	0	52.50	0.83	0.92	1.00	1.750
6	0	45.50	0.50	0.25	0.67	0.917
		52.50	0.83	0.75	0.67	1.750
8	0	45.50	0.17	0.17	0.33	0.667
		52.50	0.67	0.6	0.33	1.667
10	0	45.50	0.00	0.00	0.00	0.500
		52.50	0.50	0.58	0.00	1.583
4	1	52.50	1.00	1.00	1.00	2.000
6	1	45.50	0.67	0.50	0.67	1.333
		52.50	1.00	1.00	0.67	2.167
8	**1**	45.50	0.67	0.42	0.33	1.417
		52.50	**1.00**	**0.92**	**0.33**	**2.250**
10	1	45.50	0.50	0.33	0.00	1.333
		52.50	0.83	0.83	0.00	2.167

Chosen configuration: Impeller eye diameter of 52.50 mm with 8 blades including 4 splitter blades

WP4000 : Preliminary design of Pump



3D view of Impeller blades and splitter blades

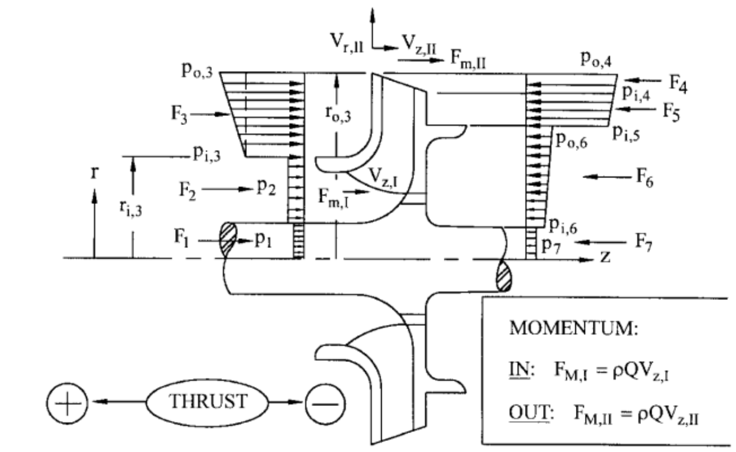


Circular projection of blades and streamlines

Chosen configuration: Impeller eye diameter of 52.50 mm with 8 blades including 4 splitter blades

WP4000 : Axial thrust and Shaft design

Forces acting on pump shaft:



$$\text{THRUST} = F_7 + F_6 + F_5 + F_4 - F_3 - F_2 - F_1 - F_{m,I} + F_{m,II}$$

For Const. - p Forces: $F_j = p_j \times 2\pi \left(r_{j,o}^2 - r_{j,i}^2\right)$ $\quad j = 1,\ldots,7$; $i = \text{inner}; o = \text{outer}$

For Linear p(r) Forces: $F_j = F_{j,const.} + F_{j,var}$

where $F_{j,var} = \frac{1}{3}\pi r_{j,o}^2 \left[2 - \frac{r_{j,i}}{r_{j,o}} - \left(\frac{r_{j,i}}{r_{j,o}}\right)^2\right] \times \left(p_{j,o} - p_{j,i}\right)$

Example:

$$F_3 = p_{i,3} \times 2\pi\left(r_{o,3}^2 - r_{i,3}^2\right) + \frac{1}{3}\pi r_{3,o}^2\left[2 - \frac{r_{3,i}}{r_{3,o}} - \left(\frac{r_{3,i}}{r_{3,o}}\right)^2\right] \times \left(p_{o,3} - p_{i,3}\right)$$

Forces over the impeller body are obtained to estimate an equivalent axial thrust on the pump shaft, which came out to be **8.14 kN.**

Estimation of permissible shaft C/S area:

A principal shear stress theory of failure proposed by Rankine (A textbook of Machine Design, Page 1525) is used to determine the shaft diameter.

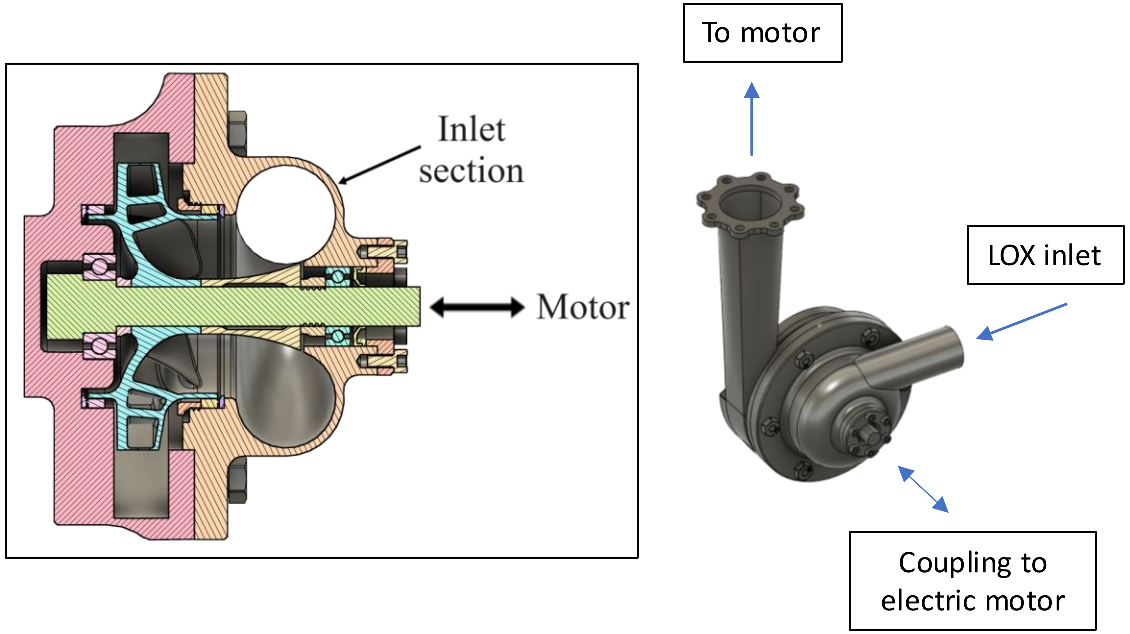
The maximum shear stress based on Bending stress (σ_b) and Torsional shear stress (τ) when a shaft is subjected to Bending moment (M_b) and Torsional moment (M_t) is given by:

$$\tau_{max} = \frac{16}{\pi d^3}\sqrt{M_b^2 + M_t^2}$$

Minimum permissible C/S area: $\mathbf{67.82\ mm^2}$

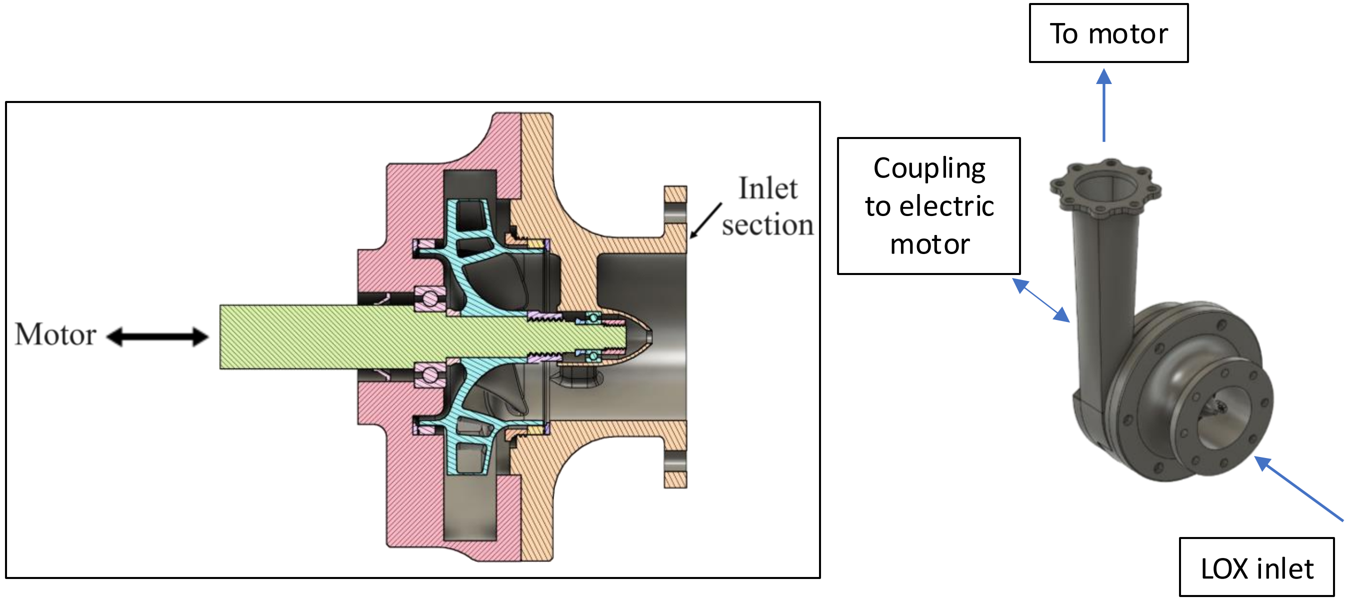
WP4000 : Pump Configurations

Configuration 1:
- Radial entry of working fluid
- Motor and inlet section placed on same side.



Advantages:
- Reduction of the pressure difference across the seal (installed where the motor shaft enters the pump body)
- Compact design

Configuration 2:
- Axial entry of working fluid
- Motor and inlet section placed on opposite side.



Advantages:
- Easy maintenance
- Balanced weight distribution
- Reduces mechanical interference

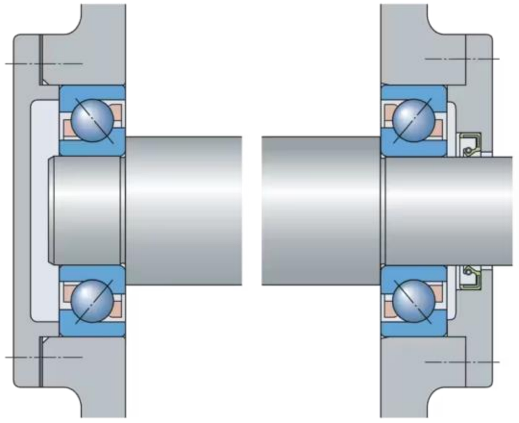
WP4000 : Selection of Bearings

A pair of angular contact ball bearings has been recommended to support pump shaft.

- **Thrust bearing:** Handles all the thrust in the system,
- **Floating bearing:** Applying preload to the bearing system

- **Hybrid:** Ceramic balls with steel rings and PTFE cage,
- **Steel version:** Steel balls with steel rings and PTFE cage

Bearing type	Inner diameter (mm)	Outer diameter (mm)	Width (mm)	Version
Floating bearing	12	28	10	Hybrid
	12	28	10	Steel
Thrust bearing	17	40	12	Hybrid
	17	40	12	Steel



Representative image for a pair of angular contact bearings

Contact pressure of 3850 MPa is observed in the bearings. (Maximum allowed contact pressure: 4000 MPa)
Future pump design iterations are necessary to reduce the axial thrust on the bearings and mitigate this risk.

Conclusions and future steps

- This programme allowed HyImpulse to lay down the base of the development of an electric Pump dedicated to Hybrid Rocket Motors, assessing linked risks and advancing its TRL by an ***in-depth analysis of a critical component***.
- A development strategy was proposed, relying on ***parallel development*** of the pump and of the drivetrain, the latter being composed of ***commercially available items***. A potential supply chain was identified to fulfil the requirements highlighted by the proof-of-concept study
- HyImpulse has identified and verified a ***cost-effective solution*** to the issue of sealing cryogenic fluids and earned valuable experience to drive an upgrade to the design.

- To further enhance the TRL, HyImpulse will focus on ***detailed component design***, purchasing of the drivetrain components and ***characterization of the pump performance*** with water and cryogenic test (Q2 2025).
- HyImpulse capabilities as engine manufacturer and launch vehicle provider, will allow the company to validate its ePump in ***integrated hot-fire tests and in flight***.